Metal ion specific capacity affinity sensor

There is a need to measure trace concentration of heavy metal ions in the environment, in medicine, in food and other products. Heavy metals are toxic

5   elements and it is therefore important to be able to determine them on the trace level. Some heavy metals, e.g. copper and zinc, are essential for the living cells. Various classical methods such as atomic absorption spectroscopy, inductively coupled plasma emission spectrometry and plasma emission mass spectrometry are in wide use. These methods require sophisticated instrumentation and skilled

10   personnel. Therefore, there is a need for easier and cheaper methods. Electrochemical methods for metal ion determination include ion selective electrodes, polarography and other voltammetric electrodes. Biosensors are selective and sensitive analytical devices and several different biosensor configurations have been described in the past for heavy metal detection. Whole cell-based biosensors

15   represent one possible design and these can utilize bacteria, yeasts, fungi, lichens, mosses and water plants as recognition element [Wittman, C.; Riedel, K.; Schmid, R. D. *Handb. Biosens. Electron. Noses*, 1997 299-332]. Another approach is to use enzymes for the detection. So far the use of apoenzymes has been the most successful and widely used method [Mattiasson, B.; Nilsson, H.; Olsson, B. *J.*

20   *Appl. Biochem.*, 1 1979 377-384]. However, these sensors are characterized by limited selectivity and fairly low sensitivity.

Protein engineering has opened up the possibility to design and produce new proteins with e. g. higher selectivity than natural ones. The fusion protein GST-

25   *Smt*A (SEQ.ID.NO.1) has been developed by protein engineering and it is reported to show a broad selectivity towards various heavy metal ions (Cu^{2+}, Zn^{2+}, Cd^{2+} and Hg^{2+}) [Shi, J.; Lindsay, W. P.; Huckle, J. W.; Morby, A. P.; Robinson, N. J. *FEBS*, 303, 1992 159-163]. Another fusion protein called *Mer*R (SEQ.ID.NO.2) is

engineered to be exclusively selective towards Hg^{2+} [Frantz, B.; O'Hallaran, T. V.; *Biochemistry*, 29, 1990 4747-4751]. A third protein, PbrR (SEQ.ID.NO.3) from the strain Alcaligenes eutrophus CH34 (The strain is deposited BCCM under the accession number LMG P-18077) is selective towards Pb^{2+}. A fourth protein, *MerP* (SEQ.ID.NO.4), is selective towards Hg^{2+}. It is believed that a large conformational change is taking place when heavy metal ions bind to these proteins. This invention describes a capacitive sensor which can detect these conformational changes directly.

Self-assembled monolayers of thiols, sulfides and disulfides on gold electrodes have been widely studied and long-chain alkanethiols are known to form insulating well-organized structures on gold substrates [Porter, M. D.; Bright, T. B.; Allara, D. L.; Chidsey, C. E. D. *J. Am. Chem. Soc* 1987, *109*, 3559-3568]. The binding formed between the sulphur atom and gold is very strong and the formed self-assembled monolayers (SAM's) are stable in air, water and organic solvents at room temperature [Bain, C. D.; Troughton, E. B.; Tao, Y.-T.; Evall, J.; Whitesides, G. M.; Nuzzo, R. G. *J. Am. Chem. Soc.* 1989, *111*, 321-335]. It has been suggested that micro-contact printing [Mrksich, M.; Whitesides, G. M. *Tibtech* 1995, *13*, 228-235] and photolithography [Bhatia, S. K.; Hickman, J. J.; Ligler, F. S. *J. Am. Chem. Soc.* 1992, *114*, 4432-4433] can be used to pattern surfaces with functionalized self-assembled monolayers for biosensor production with low cost for a diversity of applications, but until now it has not been possible to produce direct affinity sensors with high sensitivity.

Rojas et al., J. Am. Chem. Soc. 1995, 117, 336-343 relates to a capacity affinity sensor for assaying ferrocene, Per-6-thio-ß-cyclodextrin, a compound capable of forming a self-assembling monolayer, is bound to a gold surface. Monolayer defects are covered by treatment with a solution of ferrocene and pentanethiol. Steinberg et al., J. Am. Chem. Soc. 1991, 113, 5176-5182 relates to a capacity affinity sensor wich has been produced by adsorbing 2,2'-thiobis (ethylacetoacetate) or by simultaneously adsorbing 2,2'-thiobis (ethylacetoacetate) and n-pctadecyl mercaptane to a gold surface. The effect of applied potential ion binding is investigated.

Summary of the invention

It has now turned out that unexpectedly good metal ion-specific capacity affinity sensors suitable for determining the presence of a certain heavy metal ion by capacitance measurement, comprising the steps of:

a) providing a piece of a noble metal, where said piece optionally can be a rod, or alternatively a piece of insulating material such as glass, silicon or quartz, on which a noble metal is sputtered or printed;

b) providing a first SAM-forming molecule comprising a coupling group.

c) contacting the piece in step a) with the first SAM-forming molecule in step b), thereby obtaining a self-assembling monolayer on said noble metal surface;

d) contacting said self-assembling monolayer on said noble metal piece with a molecule specifically binding said heavy metal ion, thereby coupling said molecule to the self-assembling monolayer;

e) contacting the piece obtained in step d) with a second SAM-forming molecule, thereby obtaining a noble metal surface that is at least 90%, preferably at least 95%, more preferably at least 97%, and most preferably at least 99% covered with a self-assembling monolayer.

Detailed description of the invention

The detection limits reported in this invention are several orders of magnitude better than those reported previously for electrochemical metal detection methods. The insights behind this invention are that the recognition layer must be thin, well-ordered and it must cover at least 90%, preferably at least 95%, more preferably at least 97%, and most preferably at least 99% of the sensor surface. In a subsequent step, any free spots between the recognition elements are "plugged", i.e. covered with a second self-assembling monolayer-forming molecule, e.g. an alkanethiol comprising 3-25 carbon atoms preferably in a straight chain , after obtaining a self-

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assembling monolayer comprising affinity groups, thereby increasing the tightness
and insulation. A capacitive biosensor is covered by a self assembling monolayer
on which the recongnition element is immobilised toward the solution. Electrically
it is equivalent to a capacitor between the conducting metal electrode and the

5   conducting solution.

Any part of the surface that allows the aqueous solution to penetrate below the
plane where the recognition takes place will act like a short-circuiting element. The
capacitance will therefore increase due to the higher dielectric constant of the

10   penetrating aqueous solution. Oxide layers are not well ordered and it is therefore
impossible to form a dense recognition layer. Self-assembled monolayers are much
better ordered and a more perfect coverage can therefore be expected in the
immobilized layers. Furthermore, the self-assembled monolayers are much thinner
than the oxide layers, resulting in a larger capacitance in series with the capacitance

15   formed when molecules bind on the surface. This makes it easier to detect changes
in the capacitance when an analyte binds to the surface.

This invention describes an affinity sensor for monitoring heavy metal ions at trace
levels, optionally based on bioengineered proteins. A specifically heavy metal-

20   binding substance is coupled to a conducting surface via a self-assembling
monolayer. The binding of the desired heavy metal ion to said substance causes a
conformation change which is associated with a change in capacitance. The grafted
recognition layer should be electrically insulating to prevent interferences from
redox couples in the electrolyte and high Faradaic background currents. On the

25   other hand, it should be as thin as possible in order to achieve high sensitivity. The
use of self-assembled binding to gold or other self-assembling metals gives
especially thin and compact layers. The invention also shows how additional

insulation can be obtained by plugging with a different type of self-assembling molecule.

Accordingly, the present invention relates to a method for producing a metal ion
5   specific capacity affinity sensor, wherein a piece of a noble metal is covered with a layer of a self-assembling monolayer comprising affinity groups. Subsequently any free spots on the noble metal surface is covered by a second self-assembling monolayer-forming molecule.

10   In another aspect, the present invention relates to a metal ion specific capacity affinity sensor comprising a noble metal piece substantially completely covered with a self-assembling monolayer comprising affinity groups that specifically binds to a certain molecule of interest.

15   In yet another aspect, the present invention relates to a method for qualitatively or quantitatively determining the presence of a certain heavy metal ion of interest. A metal ion specific capacity affinity sensor, comprising a noble metal surface substantially completely covered with a self-assembling monolayer comprising affinity groups that specifically binds to a certain heavy metal ion of interest, is
20   contacted with a liquid sample comprising the heavy metal ion of interest and the sensor's capacitance change is determined.

In a further aspect, the present inention relates to using said sensors for analysing certain heavy metal ions of interests, such as Zn^{2+}, Hg^{2+}, Cd^{2+}, Cu^{2+} and Pb^{2+}.
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Definitions:

As disclosed herein, the terms "self-assembled monolayer" and "SAM" are synonyms and relate to the spontaneous adsorption of film components from a solution onto a solid surface making a well-ordered monolayer. Such a layer on gold substrates have previously been described [Porter, M.D.; Bright, T.B.; Allara, D.L.;

5   Chidsey, C.E.D. *J. Am. Chem. Soc.* 1987, 109, 3559-3568].

As disclosed herein, the term "noble metal" relates to a metal chosen from the group of gold, silver, copper, platinum and palladium. Gold is preferred.

10   As disclosed herein, the terms "group/molecule specifically binding to a certain heavy metal ion of interest", respectively relate to a group or a molecule which specifically binds to a certain heavy metal ion. Any molecule having such binding characteristics can be used in the present invention. Examples of such molecules are chelating compounds and certain proteins. In a preferred embodiment, the proteins

15   having the sequences according to anyone of SEQ.ID.NO. 1, SEQ.ID.NO.2, SEQ.ID.NO.3 and SEQ.ID.NO.4 are used.

As disclosed herein, the term SAM-forming molecule relates to a molecule having the ability of forming a self-assembling monolayer on a noble metal. A SAM-

20   forming molecule comprises at least one thiol, sulphide or disulphide group. Heavy metal-binding molecules, are, however, not SAM-forming molecules on their own. They must be coupled to small SAM-forming molecules in a separate step. Examples of such small SAM-forming molecules are thioctic acid and cysteamine. This coupling step is carried out after formation of the self-assembling monolayer

25   on the noble metal surface. The skilled person is well aware of how to choose suitable coupling reactions and coupling groups. In the following examples, a self-assembling monolayer consisting of thioctic acid is activated by 1-(3-dimethylaminopropyl)-3-ethyl-carbodiimide. Subsequently a heavy metal-binding

molecule is coupled to the activated monolayer. However, other similar coupling reactions are described in the litterature.

As disclosed herein, the term "plugging" refers to treatment in a solution containing

5   a thiol, sulphide or disulphide after immobilization of the affinity group either to a self-assembling monolayer on a noble metal surface or, in case the affinity molecule comprises available thiol, sulphide or disulphide groups rendering the affinity molecule to be a SAM-forming molecule per se, directly to the noble metal surface, in order to block any unblocked spots on said surface. As already mentioned, it is

10   necessary that the noble metal surface is as completely covered by a SAM as possible in order to optimize the sensitivity of the sensor.

As disclosed herein, the term "heavy metal ion" relates to metal ions having atomic numbers higher than 21, such as ions of Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Zr, Nb,

15   Mo, Ru, , Rh, Pd, Ag, Cd, In, Sn, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb and Bi. The present invention is particularly usefull for determining the presence of Zn^{2+}, Hg^{2+}, Cd^{2+}, Cu^{2+} and Pb^{2+}.

As disclosed herein, the term "functional derivatives" relates to derivatives in which

20   the original amino acid sequence has been modified or changed by insertion, addition, substitution or exclusion of one or more amino acids, as well as derivatives containing multiples of the original sequence or parts therof.

As disclosed herein, SCE stands for the saturated calomel electrode; Potentiostatic

25   perturbation means a fast change in potential. PEGDGE stands for polyethylene-glycol-di-glycidyl-ether. BSA means bovine serum albumin.

In this invention a solution containing the heavy metal ions to be determined is allowed to have electrical contact with a conducting surface containing the recognition element after which the capacitance or impedance change is determined . The capacitance change takes place between the solution and a metal surface,

5   consisting of solid metal or metal sputtered on an underlaying non-conducting surface. Faradaic reactions with the metal as well as background currents are blocked by the recognition element on the surface, eventually improved by treatment with auxiliary compounds which improve the insulation. The recognition element is bound to the metal surface, either directly through self-assembly, or by

10   binding it to a self-assembled compound on the electrode. It can also be bound through adsorption, polymerization or coating. Measurements are made by applying varying voltages to the electrode using potentiostatic methods and analyzing the current changes. The sensitivity can be improved by allowing a solution containing a secondary specific ligand to bind to the analyte already on the surface, thereby

15   increasing the size of the bound aggregate and the capacitance change.

The invention will now be described in more detail with reference to the enclosed drawings.

20   Fig. 1 shows schematically how a heavy metal specific protein is immobilized on the metal surface and how its three-dimensional conformation is changed when heavy metal ions bind to the protein.

Fig. 2 shows the measuring flow cell, a) measuring electrode, b) auxiliary platinum

25   foil electrode, c) platinum wire reference electrode, d) Ag/AgCl reference electrode.

Fig. 3 shows the response for copper for electrodes immobilized with GST-*SmtA* protein with EDC-mediated coupling (upper curve) and PEGDGE entrapment (lower curve). See example 1 for more details.

5   Fig. 4 shows the cyclic voltammetry responses recorded in a $Fe(CN)_6^{3-}$ solution when the measuring electrode was a) unmodified gold, b) gold modified with thioctic acid, c) as in b with additional modification with immobilized fusion protein GST-*SmtA* and d) as in c with additional modification with 1-dodecanethiol. More details are given in example 2.

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Fig. 5 shows capacitance change *versus* heavy metal ion concentration for a GST-*SmtA* immobilized electrode. Curve 1) shows the response for Zn^{2+}, curve 2) for Hg^{2+}, curve 3) for Cd^{2+} and curve 4) for Cu^{2+}. The measurements were performed in 100 mM borate buffer, pH 8.75 at a flow rate of 0.5 ml/min. Samples

15   with a volume of 250 μl were injected. For more details see example 3.

Fig. 6 shows capacitance change *versus* Cu^{2+} concentration for electrodes using EDC coupling of protein. Upper curve shows the signal for the GST-*SmtA*-based electrode and the lower curve represents the signal recorded by a blank electrode

20   with BSA on the surface. The measurements were performed in 100 mM borate buffer, pH 8.75 at a flow rate of 0.5 ml/min. Samples with a volume of 250 μl were injected. More details are given in example 3.

Fig. 7 shows capacitance change *versus* Cu^{2+} concentration in the range 10^{-15} M to

25   0.1 M. The measurements were performed in 100 mM borate buffer, pH 8.75 and a flow rate of 0.5 ml/min. Samples with a volume of 250 μl were injected. For details see example 3.

Fig. 8 shows a stability study for a GST-*Smt*A electrode according to the present invention. A calibration curve from 1 femtomolar to 100 picomolar was recorded each day and the total capacitance change *vs.* time was plotted. Between measurements the sensor was stored at $4^{\circ}C$ in 100 mM borate buffer pH 8.75.

5   Details are given in example 3.

Fig. 9 shows capacitance change *versus* heavy metal ion concentration for a *Mer*R immobilized electrode. Curve 1) shows the response for Cd^{2+}, curve 2) for Cu^{2+} and curve 3) for Hg^{2+}. The measurements were performed in 100 mM borate

10   buffer, pH 8.75 and a flow rate of 0.5 ml/min. Samples with a volume of 250 µl were injected. More details are given in example 4.

If a solid measuring metal electrode is used, a gold rod of typically 3 mm in diameter, is polished, cleaned and coated through self-assembly with a recognition

15   element or with a compound which can be coupled with a recognition element. A great number of coupling methods are known and may be used as suitable alternatives to those described in the examples. It is also possible to use metal sputtered or printed on glass, quarts, silicon or another insulating material as disposable electrodes. After cleaning the electrodes are coated in batch and inserted

20   in a quick-connect measuring cell. A number of different recognition elements can be immobilized on the same sputtered electrode if they are separated by insulating parts and connected to the potentiostat with switches which can be controlled by a microprocessor.

25   The inverse total capacitance is the sum of the inverse capacitances of each layer in series, i. e. the thioctic acid layer, the protein layer and the capacitance between the double layer space charge and solution. If one of these is small compared to the others, it will dominate the total capacitance. Especially if self-assembled parts give

rise to a small capacitance, it will dominate over the capacitances in the recognition layer. Changes in the recognition layer will thus have little effect on the total capacitance resulting in a low overall sensitivity of the sensor.

5   The electrode is inserted into a cell which may be either of the cuvette type or a flow cell as shown in Fig. 2. The cell must contain an auxiliary electrode, typically a platinum foil which should be placed symmetrically and opposite to the measuring electrode. A reference electrode, typically SCE or Ag/AgCl, is placed in the cell so that the voltage drop between the reference and measuring electrodes due to

10   capacitive or Faradaic currents becomes very small. In some cases the performance may be improved if a very small additional reference electrode is used, see Fig. 1c and the SCE reference is moved away, Fig. 1d. A flow cell gives more precise control over the mass transfer to the measuring electrode and injection of sample and cleaning up is more easily automated. Flow cells with volumes of 2 ml and 10

15   µl were found to have about the same sensitivity. A flow cell with disposable electrodes made by sputtering gold on silicon also had similar properties.

The electrodes are connected to a fast potentiostat which in turn is controlled by a microprocessor. The potentiostat will keep the measuring electrode at a pre-set

20   value *versus* the reference electrode. A potentiostatic perturbation is imposed on the measuring electrode. It may be a sinusoidal wave, it may be a step voltage or any other wave-form which enables interpretation of the results. The currents caused by the perturbation voltage are used for evaluation of the capacitance of the measuring electrode. It can be done for sinusoidal perturbations by separating the in-phase and

25   out-phase part of the current in a lock-in amplifier. If this is repeated at different frequencies an impedance spectra can be obtained. In all cases the capacitance can be evaluated from the current responses. As usual in electrochemistry the role of current and potential can be reversed, i. e. a galvanostatic step in current will cause

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the potential to change. This change can be used for evaluation of the capacitance, although using different algorithms.

A known volume of sample is normally mixed with a known volume of a

5   conducting liquid in e.g. a cuvette in a batch type cell. For a flow cell, a known volume is injected into a conducting carrier flow pumped with a distinct flow rate. The conducting liquids are normally buffers with ionic strengths from a few millimolar and up. The sample can be in a non-conducting medium but a conducting solution must fill the cell when measurements are made.

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The present invention will now be further described with reference to the following examples. The examples are given for the purpose of information and are not intended to limit the scope of the present invention.

Example 1.

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The fusion proteins GST-$SmtA$ and $MerR$ were produced as described below and dissolved in phosphate buffered saline (70 mM NaCl, 1.3 mM KCl, 5 mM Na_2HPO4, 0.9 mM KH_2PO_4, pH 7.3) containing 50 % (v/v) glycerol to a final concentration of 1 mg/ml protein. Thioctic acid and glutaraldehyde were purchased

20   from Sigma and 1-(3-dimethylaminopropyl)-3-ethyl-carbodiimide hydrochloride was obtained from Fluka. 1-dodecanethiol and the gold rods used for the electrodes (Cat. No 26,583-7, = 3 mm) came from Aldrich Chemicals. The heavy metals $CuCl_2$ *$2H_2O$, $ZnCl_2$, $HgCl_2$ and $Cd(NO_3)_2$*$4H_2O$ were all from Merck (Darmstadt, Germany). PEGDGE was achieved from Polysciences Inc. (USA). All

25   other reagents used were of analytical grade.

The biosensors were prepared by immobilizing fusion proteins on the gold surface by EDC-mediated coupling, PEGDGE entrapment or glutaraldehyde coupling. In all

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cases 20 µl of the dissolved fusion proteins were diluted with 480 µl 100 mM borate buffer, pH 8.75 and the solution was ultrafiltered on a micro-filter (Amicon, USA) with a molecular cut-off of 3000 D. After the ultrafiltration the filter was turned over to recover fusion protein and its concentration was adjusted to 0.04 mg/ml in

5   borate buffer. Gold electrodes were cleaned and pretreated with self-assembling of thioctic acid, as described earlier by Berggren and Johansson [Berggren, C., Johansson, G., *Anal. Chem.*, Submitted]. As the *Mer*R protein is sensitive against oxidation in air, the preparation of these electrodes was performed under nitrogen atmosphere.

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EDC-mediated coupling: The self-assembled electrodes were thoroughly washed with ethanol, dried and thereafter activated in a 1 % solution of 1-(3-dimethylaminopropyl)-3-ethyl-carbodiimide hydrochloride in dried acetonitrile for 5 hours. After washing with 100 mM borate buffer, pH 8.75 the electrodes were

15   dipped into the protein solution at a temperature of 4°C for 24 hours. Subsequently each electrode was thoroughly washed with borate buffer and dipped into a solution of 1-dodecanethiol for 20 minutes.

PEGDGE entrapment: The thioctic acid activated electrode was covered with 1.5

20   µl of a 0.04 mg/ml protein solution in 100 mM borate buffer containing 30 % (w/w) PEGDGE and the electrode was incubated at 45°C for 15 minutes. Afterwards the electrode was treated with 1-dodecanethiol for 20 minutes, washed with borate buffer and placed in the measuring cell.

25   *Glutaraldehyde coupling:*   Prior to glutaraldehyde immobilization the electrode was modified with cysteamine, instead of thioctic acid. The dried electrode was dipped into a solution containing 12.5 % (w/v) glutaraldehyde in coupling buffer (0.1 M sodium phosphate, 0.15 M NaCl, pH 7) and 6 g/l $NaCNBH_3$

for 4 hours. Then, the electrode was washed thoroughly with coupling buffer and dipped into the protein solution (0.04 mg/ml) with 6 g/l $NaCNBH_3$ for 4 hours. Finally the electrode was washed thoroughly with coupling buffer before use.

5   *Capacitance measurements:* The biosensor was arranged as the working electrode in a three-electrode system connected to a fast potentiostat, as shown in figure 1. It was placed in a flow cell with a dead volume of 10 µl which was built in house. A platinum foil served as the auxiliary and a platinum wire as the reference electrode. An extra reference electrode (Ag/AgCl) was placed in the outlet stream, as the

10   platinum does not have a defined potential. The buffer solution was pumped by a peristaltic pump with a flow rate of 0.5 ml/min. through the flow cell. Samples were injected into the flow *via* a 250 µl sample loop. The buffer used was 10 mM borate, pH 8.75. Before use it was filtered through a 0.22 µm millipore filter and degassed.

15   The working electrode had a rest potential of 0 mV vs. the Ag/AgCl reference electrode. When measuring, a potential step of 50 mV was applied and the current transient that followed when the potential increased was assumed to follow the equation:

20 $$i(t) = u/R_s \exp(-t/R_s * C_1) \qquad (1)$$

where $i(t)$ is the current at time t, u is the amplitude of the potential pulse applied, R is the resistance between the gold electrode and the reference electrode, C_1 is the

25   total capacitance over the immobilized layer and t is the time elapsed after the potential pulse was applied. The current values were collected with a frequency of 50 kHz and the first ten values were used in the evaluation of the capacitance. Each capacitance value was calculated as the mean of ten measurements.

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With capacitance measurements the interface between a conducting electrode and the sample solution is studied. This interface is called the electrical double-layer as charges and dipoles will orient with opposite signs on the conducting surface and in the solution. When the heavy metal specific protein is immobilized on the electrode surface it will exchange the buffer solution at the surface and a charge separation will take place, leading to a decrease in capacitance. The detection principle used in this work is based on monitoring a conformational change resulting from a specific binding of a certain heavy metal ion to an immobilized protein on the electrode surface (see Fig. 2). As the sensor measures changes in conformation, it is important to optimize the immobilization conditions.

Immobilization of the recognition element: A gold electrode was used as conducting noble metal surface in this work. To immobilize the recognition elements, which were different fusion proteins, the gold surface had to be modified in some way. A well-known and easy method is to use self-assembling of thiol-, sulphide- or disulphide compounds onto the gold surface. Self-assembling is a spontaneous process producing well-ordered monolayers of molecules. Furthermore the binding between sulphur and gold is rather strong, an important stability aspect in biosensor design, where leaking off of the recognition element results in loss of activity. Three different immobilization methods were studied in order to produce an optimal surface for capacitance measurements, namely; EDC-mediated coupling, PEGDGE entrapment and glutaraldehyde coupling. In all cases a short compound containing one or more sulphur groups was first self-assembled on the gold surface. The EDC-mediated coupling is producing a monolayer of protein molecules on the surface without any crosslinking between individual molecules. This method has previously been shown to be successful for immobilization of antibodies onto gold electrodes with self-assembled thioctic acid on the surface [Duan, C.; Meyerhoff, M. E., *Anal.*

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Chem., 66, 1994, 1369-1377]. With PEGDGE immobilization the protein will be entrapped in a polymer network, where the heavy metals can diffuse into the pores of the polymer. Calibration curves for copper are shown in figure 3 for EDC coupling (upper curve) and for PEGDGE entrapment (lower curve) of the protein. It

5 was found that the sensitivity was much higher for the EDC activated electrode. A possible explanation might be that the PEGDGE entrapment prohibits the conformational change of the fusion protein to some extent. The reproducibility was also lower for the PEGDGE electrodes, because of the difficulty to deposit exactly the same amount of the protein/crosslinker for each electrode. Further experiments

10 will be performed with less concentration of PEGDGE to decrease the crosslinking and thereby produce a less rigid protein layer. Glutaraldehyde is also a crosslinker, but in this case the surface was first activated by glutaraldehyde before the protein was added. Also in this case it is very important to optimize the amount of crosslinker in order not to crosslink the protein too much, making it rigid and not

15 susceptible to conformational changes. All further experiments were performed with electrodes manufactured by the EDC method.

Example 2

Cyclic voltammograms were recorded in 5 mM $K_3[Fe(CN)_6]$, 1 M KCl in a batch
cell, with the unmodified/modified gold electrode as working electrode a SCE as
5   reference and a platinum flag as auxiliary electrode. The scan rate was 50 mV/s.
The electrodes were connected to a Princeton Applied 274 A potentiostat, connected
to a computer.

In order to develop a sensitive affinity sensor based on capacitance measurements
10   the immobilization layer has to be as thin as possible and well-ordered. Defect sites
in the monolayer might lead to penetration of solution molecules through the layer
and close to the metal surface, leading to short-circuiting of the recognition layer
with highly conducting aqueous channels. The result will be that capacitance
changes will be smaller or absent for such defect sensors. The importance of good
15   insulation of the electrode surface has earlier been demonstrated [Berggren, C.;
Johansson, G. *Anal. Chem.* Submitted]. The degree of insulation can be studied by
having a small permeable redox couple in solution. In figure 4 it is shown how the
blocking increases for each additional layer. For a clean gold surface the redox
couple $K_3[Fe(CN)_6]$ is oxidized and reduced at the metal surface. A surface
20   covered with self-assembled thioctic acid reduces the access to the surface.
Immobilization of the protein further insulates the surface, but it is not until the
treatment in 1-dodecanethiol that the oxidation/reduction peaks totally disappears.
All electrodes in the following experiments were therefore treated twenty minutes
with 1-dodecanethiol.

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Example 3

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Characteristics such as sensitivy, selectivity, response time, stability and electrode surface regeneration possibility were studied in this work. However, the GST-SmtA based electrodes were more thoroughly studied, but some characteristics were studied for MerR protein based electrodes as well, and obtained results were

5   evaluated and compared. The affinity of the GST-SmtA protein was studied for copper, cadmium, mercury and zinc (see Fig. 5). The electrodes responded for all four metal ions with decreasing sensitivity for Cu > Cd > Hg > Zn, well in agreement with previously reported results obtained with solution of this engineered protein [Shi, J.; Lindsay, W. P.; Huckle, J. W.; Morby, A. P.; Robinson, N. J. *FEBS*,

10 303, 1992 159-163]. The detection limit was in the femtomolar molar range or below for each of the studied heavy metals. Reference electrodes, equally prepared but using BSA instead of GST-SmtA resulted in hardly detectable signals for Cu and no signals at all for the other ions (see Fig. 6). Similar results were obtained when using another protein, urease, well known to bind heavy metals. For the latter

15 case, the absence of any detectable signals was assumed to be due to lack of conformational changes upon exposure to heavy metal.

The activity of an GST-SmtA electrode was studied for an extended interval. Copper samples of concentrations of 10^{-15}M to 0.1 M were injected and the

20 capacitance changes were determined. A slow increase of the signal was obtained to approximately 10^{-5}M thereafter the signal increase became much faster to approximately 10^{-2}M, where saturation occurred (see Fig. 7). It is believed that the increase in the first part of the curve is due to the specific binding of heavy metal and that the second one probably is due to denaturation of the protein on the

25 electrode surface. Inability to regenerate the electrode after injection of a 1mM copper might support this assumption. The stability of the GST-SmtA based biosensor was studied for 16 days. A calibration curve between 10^{-15}M to 10^{-10}M Cu was measured each day and the total capacitance change vs. time is plotted in

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figure 8. Between measurements the sensor was stored at 4°C in 100 mM borate buffer, pH 8.75. A loss of activity was observed after 10 days and it decreased with approximately 40% after 16 days.

5   The surface of the biosensor could be regenerated by injecting 250Tl, 1 mM EDTA. It was found that if EDTA was injected just before storage the biosensor lost acitivity over night, but if thc electrode was stored with heavy metal and the regeneration procedure took place immediately before measuring hte next day no activity loss could be observed. The observed phenomenon was attributed to the

10   assumption that the protein has a more open structure when the heavy metal ion is absent and hence this structure is more easily denatured. Regeneration with EDTA after injection of a sample containing as much as 1 mM Cu^{2+} was unsuccessful, attributed to irreversible surface denaturation by this high metal ion concentration.

15   <u>Example 4</u>

Biosensors were constructed using the second engineered protein, MerR, and signals were recorded for Cu, Cd, Hg and Zn. This protein was reported to be highly specific towards mercury (II) ions [Frantz, B.; O'Hallaran, T. V.; *Biochemistry*, 29,

20   1990 4747-4751]. The protein was immobilized onto the gold surface only by using the EDC-coupling method. Obtained results were in good agreement with reported properties, the MerR-based electrodes displayed highest selectivity for mercury and that this electrode showed higher selectivity than the GST-SmtA based electrodes (see Fig. 9).